Cryogenic Fluid Management Technology for Exploration

DLT Forum Presentation

April 7, 2006

RTP/Propellant Systems Branch
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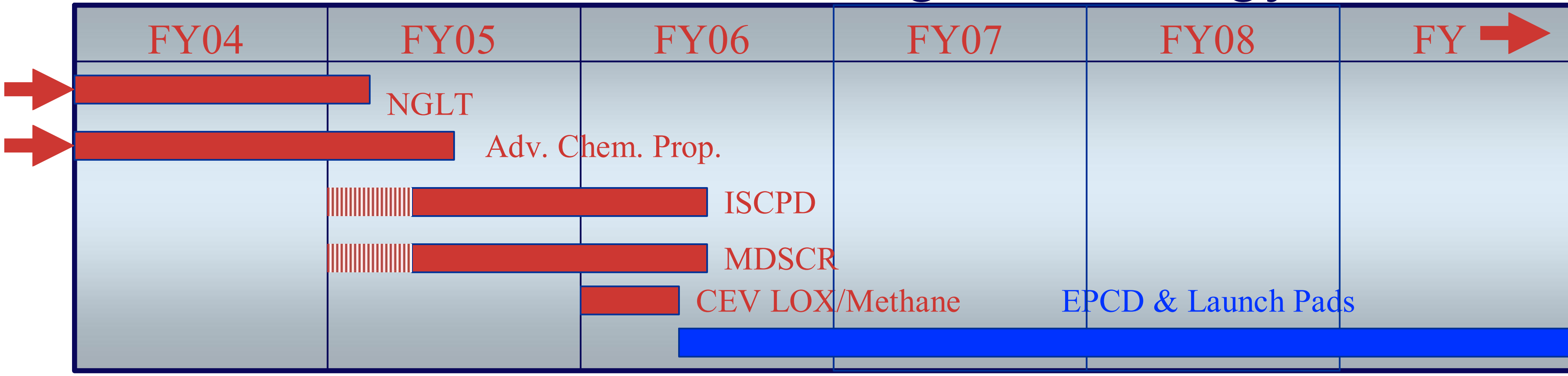
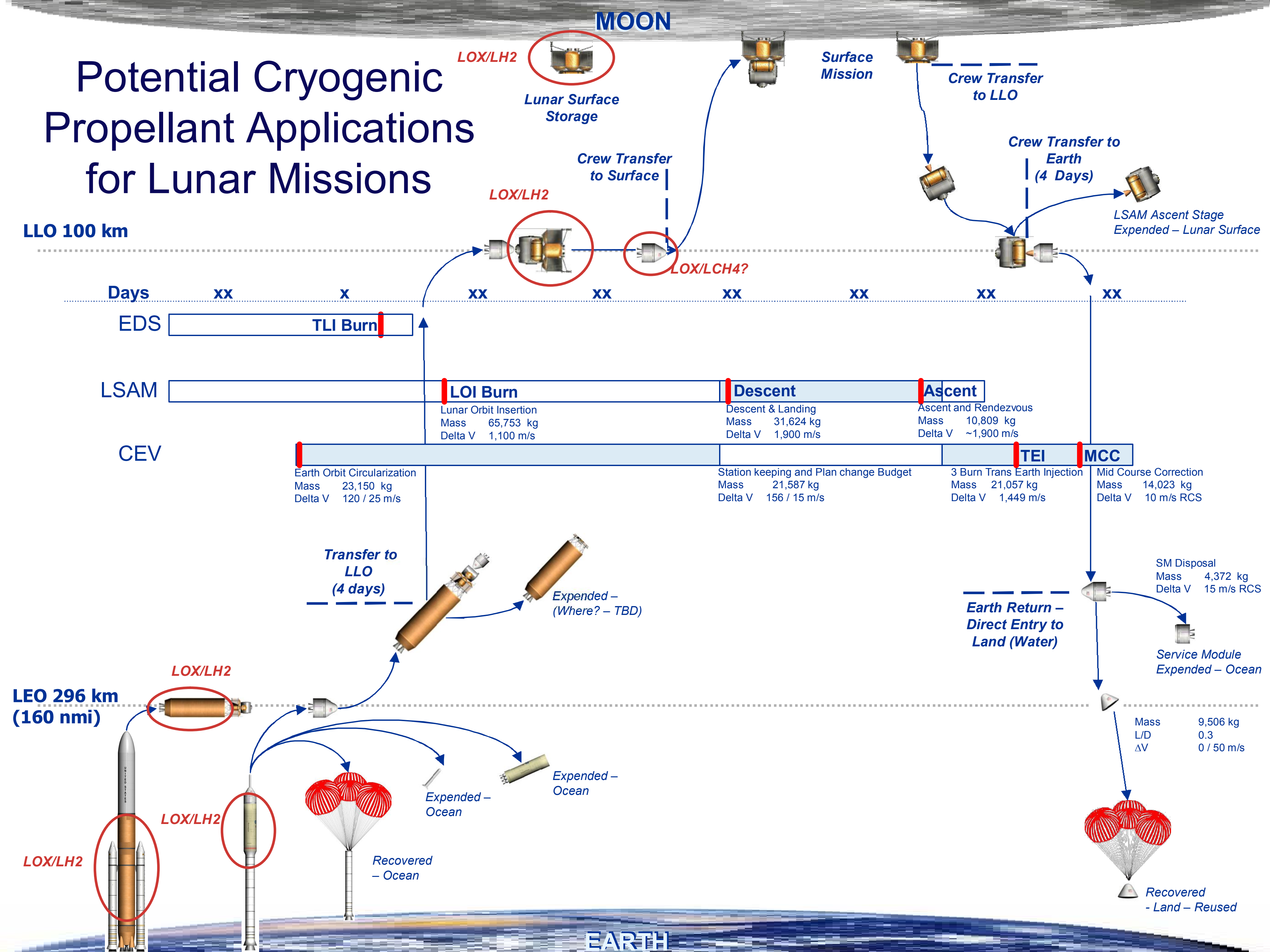
Recent CFM Funding Chronology



- Next Generation Launch Technology Program (NGLT)
- In Space Propulsion Project (ISPP), Advanced Chemical Propulsion
- Exploration Systems Research and Technology Program (ESR&T), In-Space Cryogenic Propellant Depot Project (ISCPD)
- Exploration Systems Research and Technology Program (ESR&T), Maturation of Deep Space Cryogenic Refueling Technologies (MDSCR)
- Crew Exploration Vehicle (CEV) LOX/Methane Propulsion Advanced Development
- Exploration Propulsion and Cryogenic Development (EPCD) Project (Exploration Technology Development Program)

- Launch Pad Cryogenic Propellant Systems Developments (Kennedy Space Center tasks)

Potential Cryogenic Propellant Applications for Lunar Missions

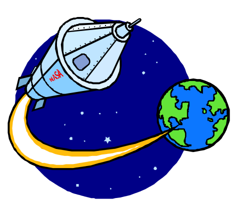


In-Space Cryogenic Propellant Systems

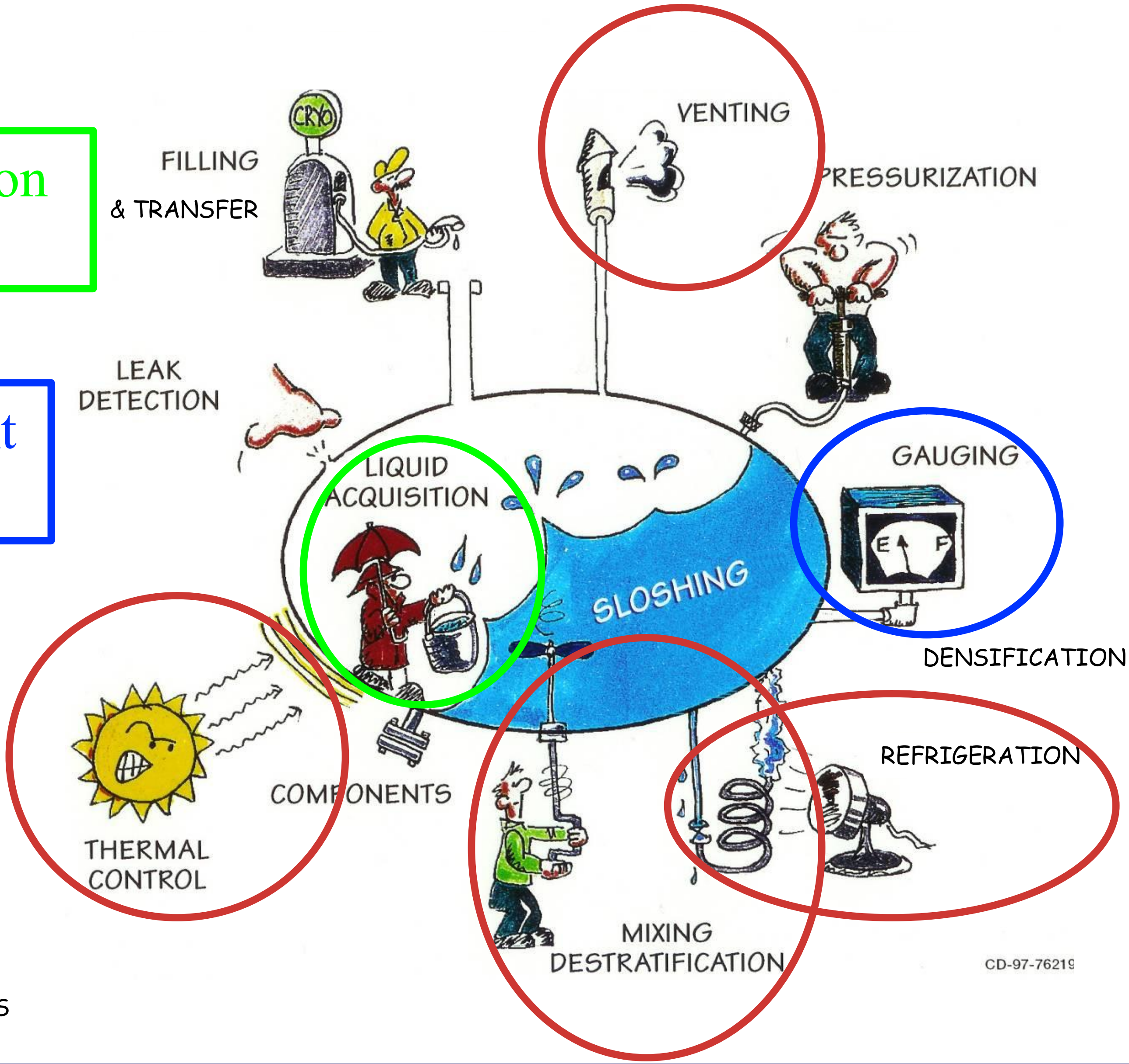
Liquid Acquisition Devices

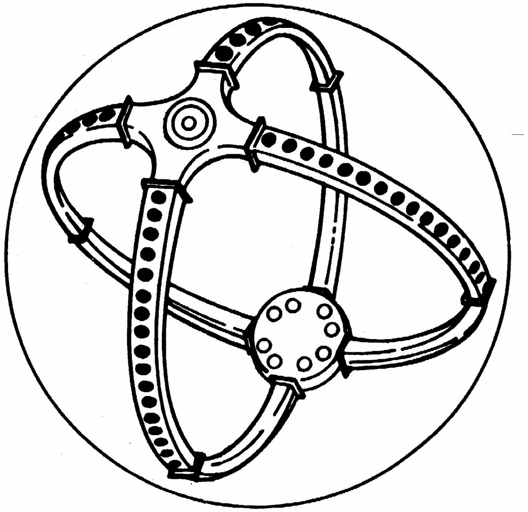
Low-g Propellant Gauging

Long-Term Storage



LOW GRAVITY EXPERIMENTS





Liquid Acquisition Devices (LADs)

Maureen Kudlac

Background

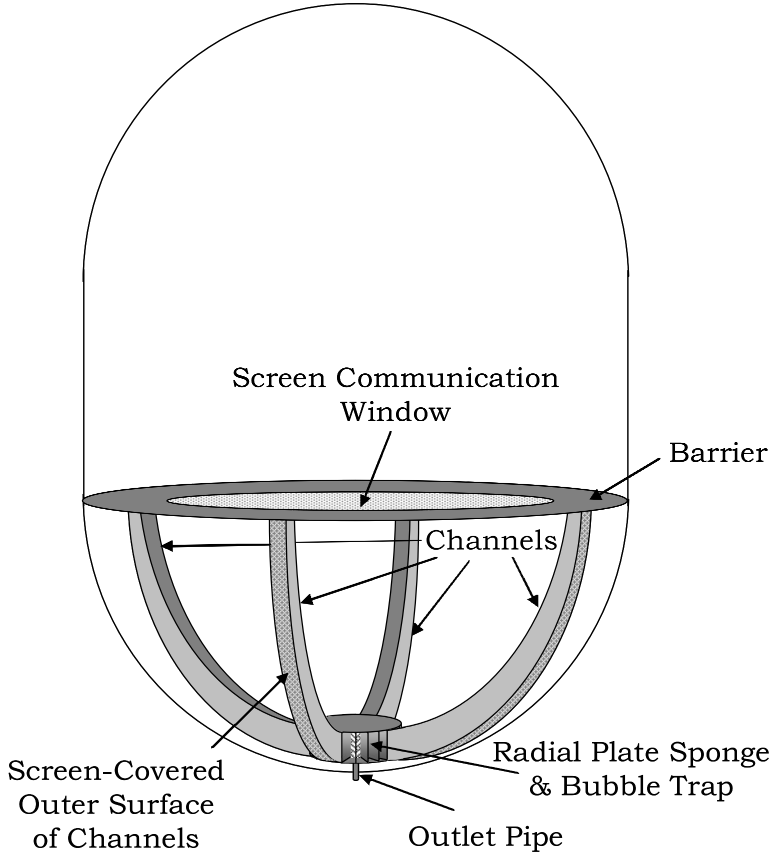
- The acquisition and expulsion of single-phase propellant in orbit can be challenging
  - Capillary screen liquid acquisition devices (LAD's) are used extensively in storable propellant propulsion (e.g. Space Shuttle Reaction Control System/Orbital Maneuvering System (RCS/OMS)
- There is currently a lack of data in *cryogenic* LAD's
  - Complex low gravity fluid behavior, thermodynamics, and heat transfer
- Cryogenic propellant transfer in orbit could necessitate LAD's, i.e., enables efficient to transfer single phase liquid

Progress

- Cryogenic LAD development is a joint MSFC/GRC program dating back to the late 1990’s
  - Progress to date
    - *Bubble point testing in isopropyl alcohol (IPA), liquid nitrogen (LN2), liquid hydrogen (LH2), and liquid oxygen (LO2) (GRC)*

      (IPA and LN2 are reference fluids)
    - Screen manufacturing variability tests (MSFC)
    - Heat Entrapment Experimentation (MSFC)
    - *Screen channel outflow testing in IPA, LN2, LH2, and LO2 (GRC)*

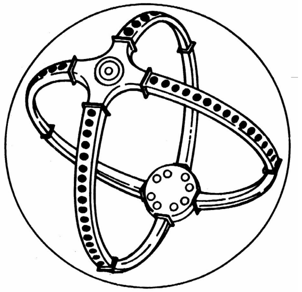
Propellant Management Devices (PMD)



- Compartmentalized tank used to position bulk propellants.
- Capillary screen channels allow passage of vapor-free liquid from tank into feed system outlet
- Screen channel LAD is one type of PMD

Screen Channel LAD

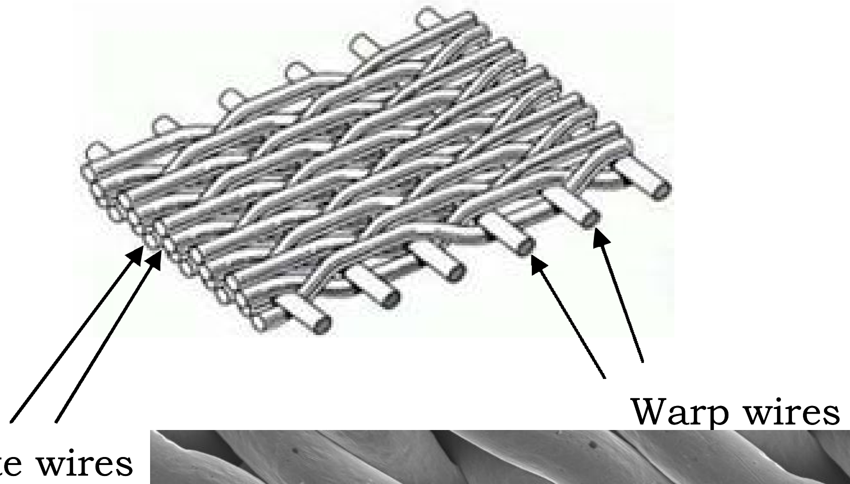
- LADS closely follow the contour of the wall (typically within 0.635 cm) of the propellant tank
- Either a rectangular or a triangular cross-section.
- The channel side that faces the tank wall has multiple openings that are covered with tightly woven screen.
- Surface tension forces of liquid trapped in the tightly woven screen inhibits gas flow across the screen and provide single phase propellant flow

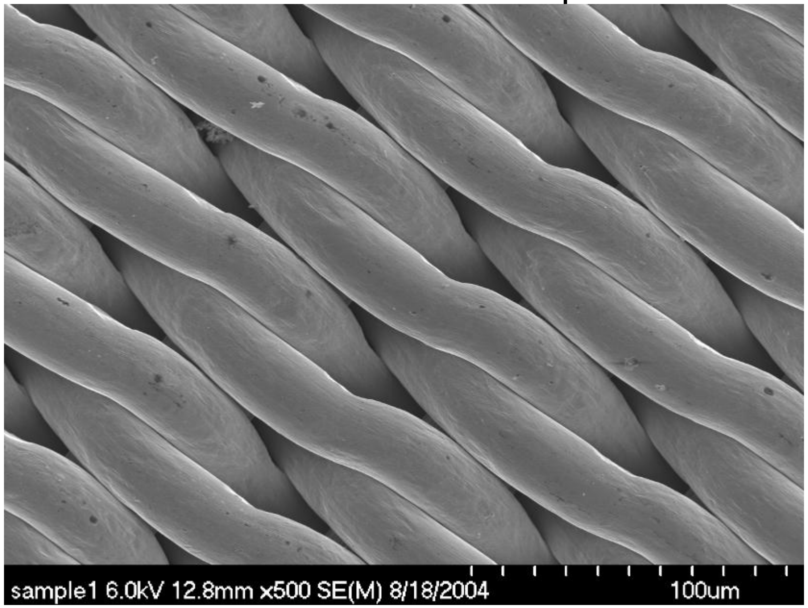


Screens

Twill Dutch: Each shute wire successively pass over and under two of the warp wires. This weave type places successive shute wires very close to each other, resulting in a tightly woven filter cloth with very small tapered or wedge shaped openings.

[With acknowledgments to the Newark Wire Cloth Company]





Scanning Electron Microscope (SEM) photo of a 200x1400 screen

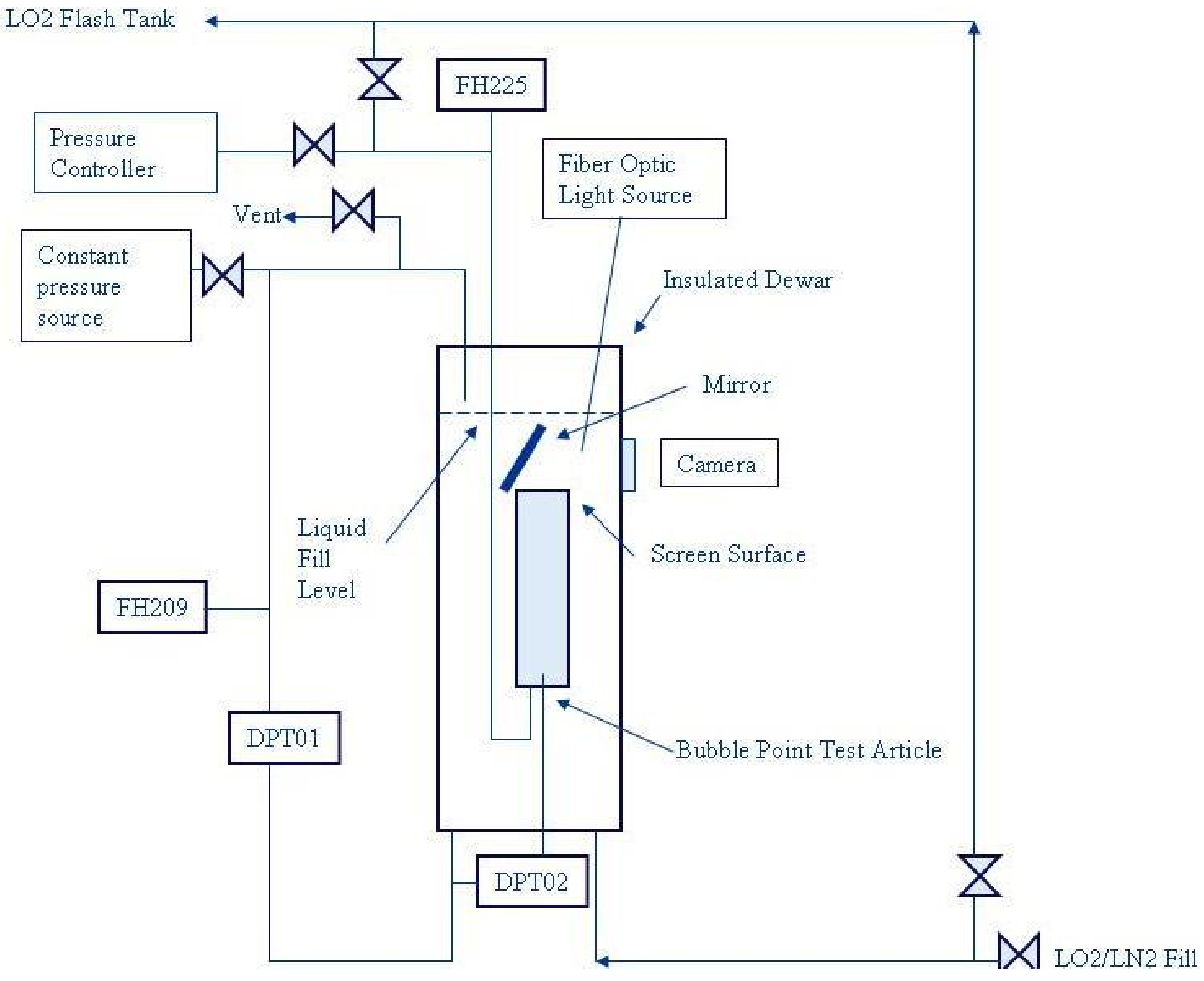
Bubble Point Tests

- Bubble point is measure of screen resistance to vapor flow across the screen

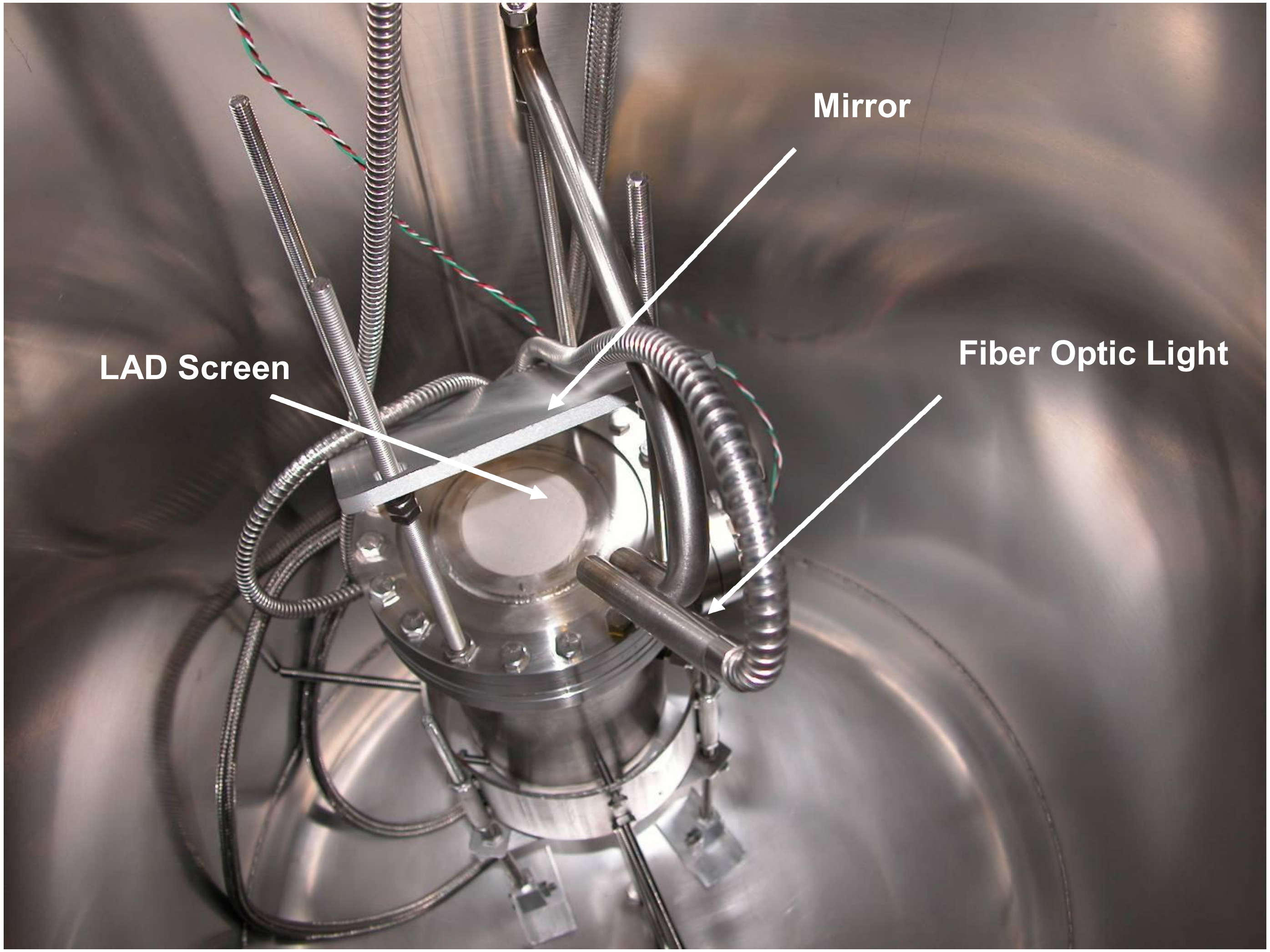
- Bubble point testing used as acceptance tests for screen type devices.
  - Tests typically done in isopropyl alcohol (IPA).

  - Comparison of bubble point data to historic IPA data validates manufacturing and test techniques.

Bubble Point Test Hardware



Bubble Point Test Article Installed in Cryogenic Dewar



Results and Discussion – Bubble Point

	IPA	LN2		LH2		LO2	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
200x1400 (inches H20)	**15.5**	6.2	**6.6**	1.4		9.3	**9.5***
325x2300 (inches H20)	**24.18**	9.6	**10.7**	2.1	**1.7**	14.5	**14.11***
Surface Tension (N/m)	0.022	0.00875		0.001945		0.0132	

Preliminary observation indicate that experimental data agrees with predicted bubble point based on surface tension (extrapolation of IPA data)

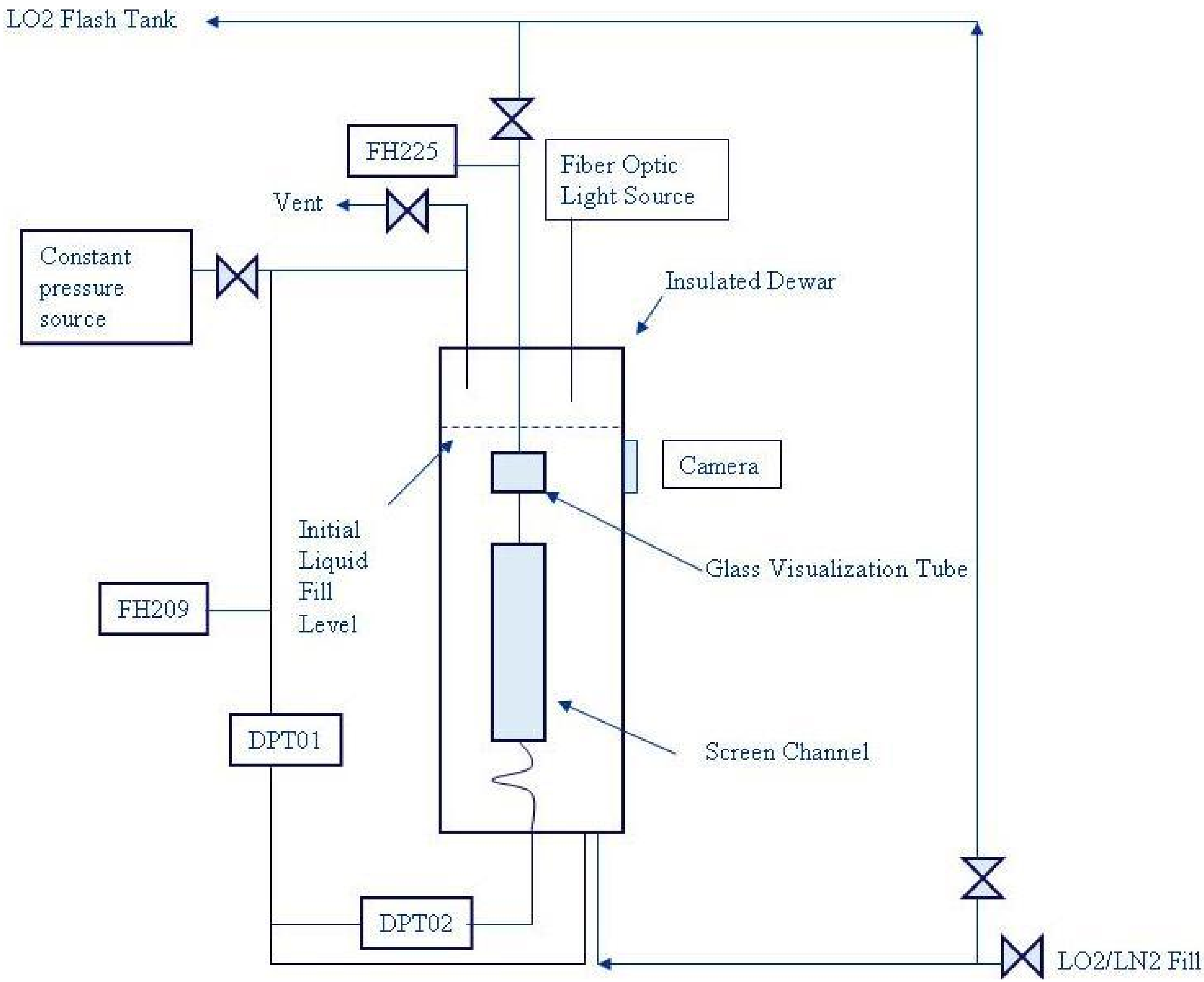
* *Preliminary observation*

1 inch of water ~ 0.04 psi

Screen Channel Outflow Test Approach

- Rectangular Screen Channel
  - 20 inches long by 1.5 inches wide by 1 inch deep.

LN2/LO2 Outflow Test Set up



Results and Discussion – Screen Channel Outflow Test Results

- Flow rate varied between 0.06 and 0.25lb/sec.
- In most cases gas ingestion occurs when system pressure loss approaches bubble point pressure.
- Main contributions to break down appear to be exposed channel height and differential pressure across the screen resulting from flow.

LAD Test Results Summary

- LO2 bubble point test data indicates indicates consistency with pre-test predictions and historical data.

- Screen channel LO2 & LN2 outflow testing validated test setup, indicates breakdowns near screen bubble point ΔP. Represents first known channel outflow testing with LO2

Screen Channel LAD – Future Work

- Continue gathering fundamental data on various potential propellants (including LH2, liquid methane (LCH4), and LO2)

- Performing preliminary Heat Entrapment Testing with LN2

- Determining the effect of autogenous/non-autogenous pressurants on LADs

- Developing/validating robust analytical models to predict the performance of cryogenic LADS

Screen Channel LAD – Future Work
continued

- Developing / testing flight LAD designs to validate LAD manufacturing techniques and LAD performance at flow rates expected for a specific application

- Developing/validating techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and changes in tank pressure.
  - Include the use of heat sinks from recirculators, active cryocoolers or gas in the thermodynamic vent

- Developing a low-g experiment to anchor models with flight data

Liquid Quantity Gauging Technologies for Cryogenic Propellants in Low-Gravity (Mass Gauging)

Neil T. Van Dresar

Low-g Liquid Quantity Gauging

- Objective
  - Measure cryogenic liquid quantity in a propellant tank in low-gravity without resorting to propellant settling
  - The gauging device should have:
    - High accuracy
    - Low power consumption
    - Low weight and volume
    - High reliability
- Benefits
  - Reduced propellant margins (reduced spacecraft size & weight)
  - No propellant consumption during gauging measurement
  - Reduced disruptions to nominal spacecraft operation
  - Diagnostic functions such as leak detection

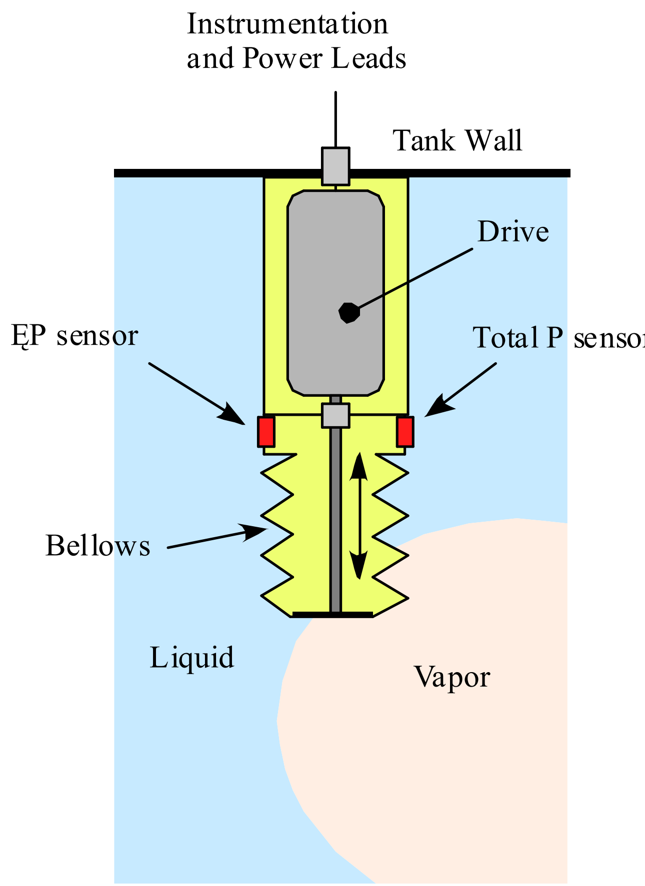
GRC Low-g Liquid Quantity Gauging Development Approach

- Parallel development of four concepts currently underway
  - Compression Mass Gauging (CMG)
  - Optical Mass Gauging (OMG)
  - Pressure-Volume-Temperature method (PVT)
  - Radio Frequency (RF) gauging
- Perform ground tests to demonstrate proof of concept and advance TRL
  - All concepts are at TRL~3-4 (Proof-of-concept or laboratory breadboard validation)
- Conduct flight experiments
  - No <u>cryogenic</u> liquid gauging method has been proven in low-g
    - TRL 5 requires validation in relevant environment

Compression Gauging Concept
(Southwest Research Institute, GRC)

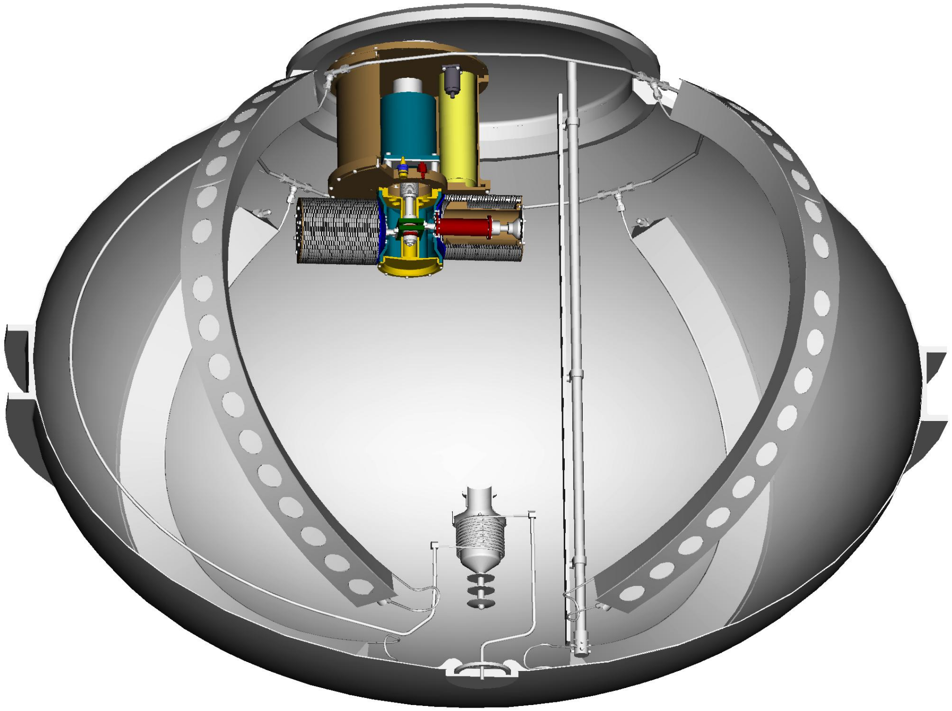
- The compression gauge operates on the principle of slightly changing the volume of the tank by an oscillating bellows
- The resulting pressure change is measured and used to predict the volume of vapor in the tank, from which the volume of liquid is computed

$$V_{vapor} = -\gamma_o \Delta V_{swept} \frac{P}{\Delta P}$$



Compression Mass Gauge for LH2
(built by SwRI)

Flight-like Gauge



Gauge in Spacecraft Tank

Status & Issues with Compression Gauging

Status

- Extensive history of cryogenic ground testing with breadboard hardware (±3% accuracy for LN_2 & LH_2)
- Flight-like hardware has been built, but not yet tested

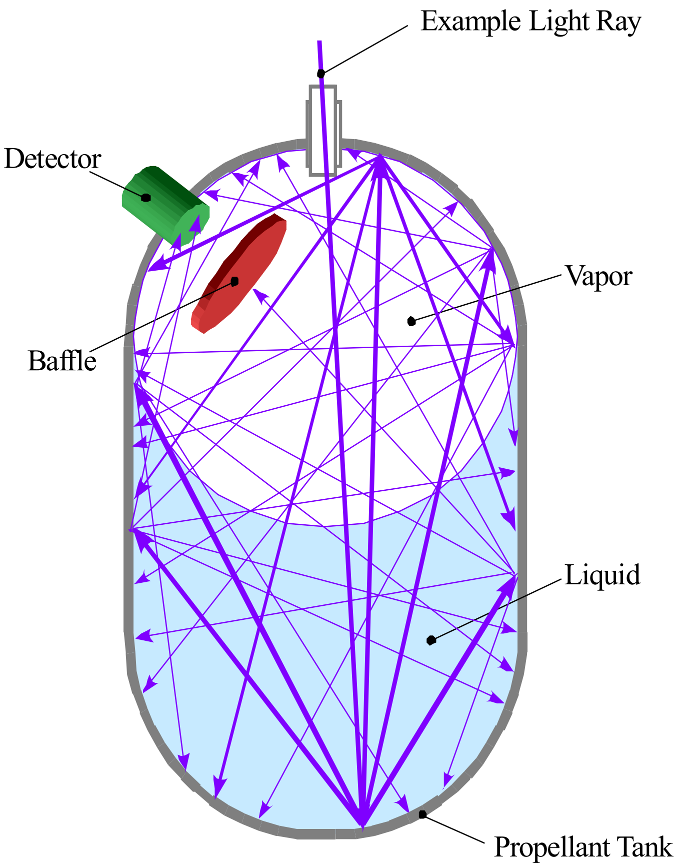
Issues

- CMG is mechanically complex; weight and volume are greater than desired
- Cyclic-pulse mode may cause acoustic resonances in certain conditions
- Single-pulse mode is back-up operational mode, but remains to be tested
- Dynamic pressure transducer improvements needed

Optical Gauging Concept

(Advanced Technologies Group, MSFC, GRC)

- Light introduced into a closed container with reflective walls (an optical integrating cavity) will travel in random paths before reaching a detector
- In theory, the random light paths produce a uniform internal light intensity
- Light is attenuated by liquid whereas vapor has a negligible effect
- Detector output is inversely proportional to liquid mass



Status & Issues with Optical Gauging

Status

- Optical gauging demonstrated in small and large scale cryogenic tanks at MSFC (in 1-g)
- Fundamental studies underway at GRC (experimental & modeling)

Issues

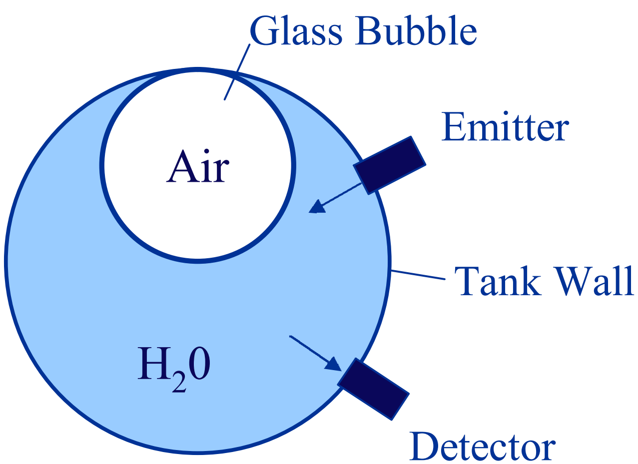
- Is tank acting as an integrating cavity or were the MSFC tests actually a line-of-sight or first reflection measurement?
- How important are tank wall optical properties?
- Do internal objects have an effect?
- Does tank orientation have any effect in 1-g?
- Low maturity of numerical simulation model is a limitation
  - In principle, the model could be used to conduct parameter-space study and guide development

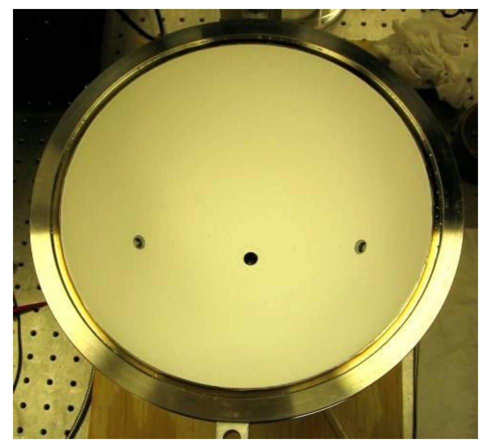
Bench-Top Optical Gauge Testing at GRC

Test Tank & Stand

Glass Bubbles

Mill Finished Surface

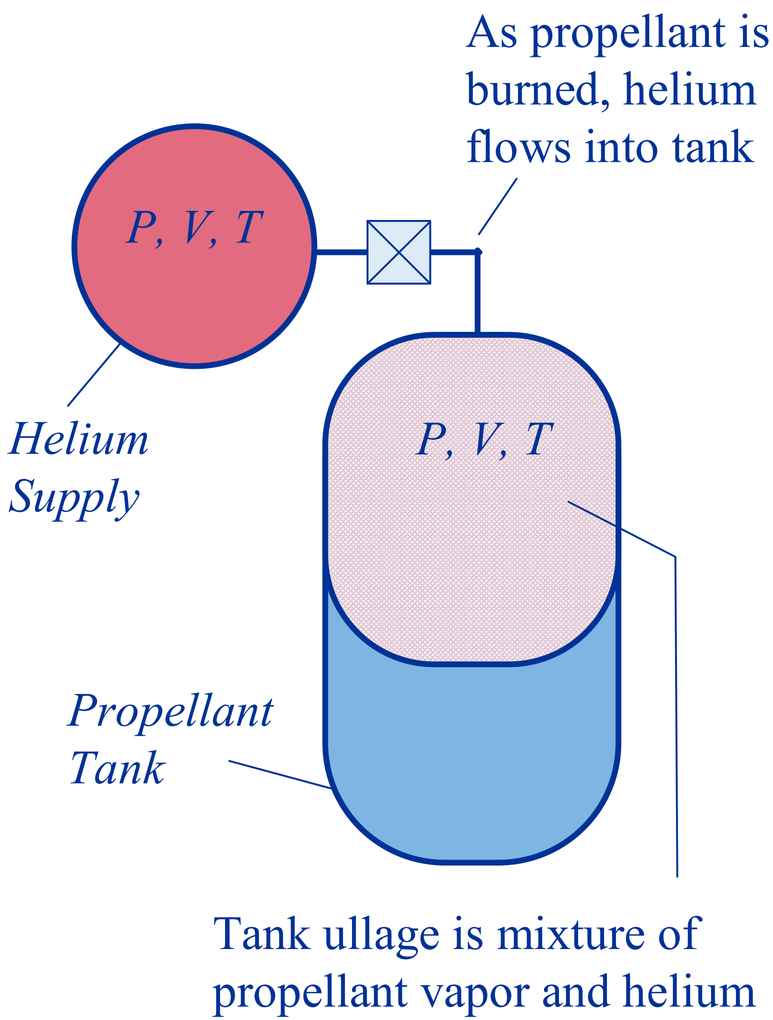




Ideal Optical Surface

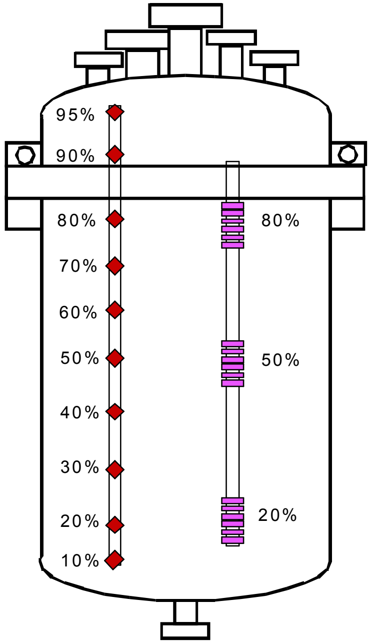
PVT Gauging Concept

(Neil Van Dresar, P.I., GRC)



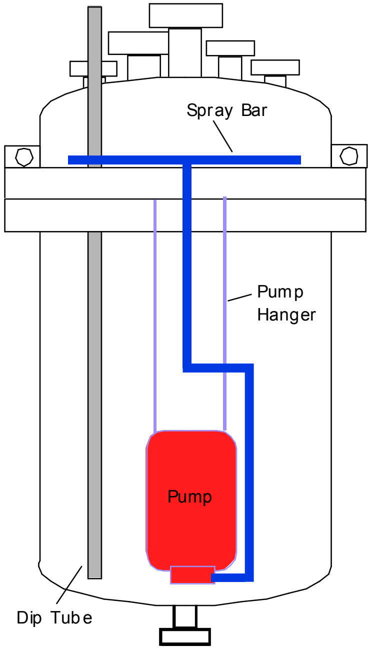
- PVT is a gas law method based on conservation of mass of the pressurant gas used to pressurize the propellant tank
  - Used on shuttle RCS & communication satellites
  - Requires use of a non-condensable pressurant (GHe)
- Applicable to cryogens, but has only recently been demonstrated
  - Tank ullage will contain a significant amount of propellant vapor
- Attractive because it may require no additional hardware or tank penetrations

PVT Tests with LN2 at GRC (2004)



Closely-Spaced Silicon Diode Array

Internal Silicon Diode



6 ft^3 tank

± 3% accuracy

Status & Issues with PVT Gauging

Status

- Accuracy deemed marginal on the basis of analytical studies and ground tests for LN2/LO2 (and LCH4, since properties are similar)
- Further testing at GRC in 2006 with LO2 and LH2
  - CEV project, was initially LO2/LCH4
  - Some small-scale LCH4 testing also planned

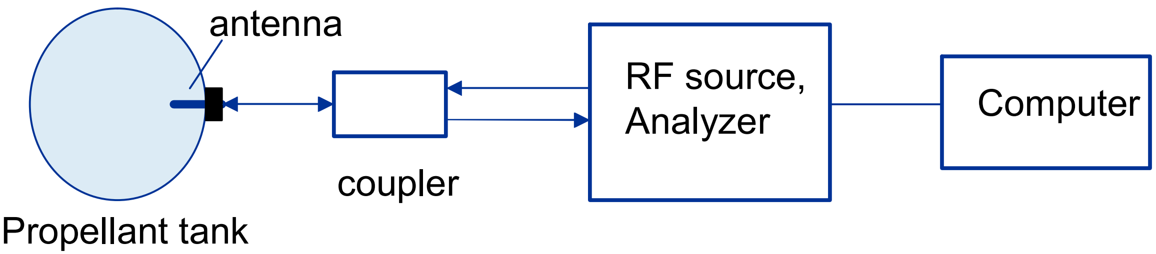
Issues

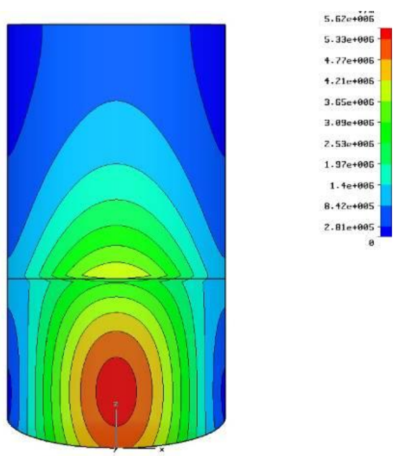
- Uncertainty analysis results indicates PVT accuracy may lack desired accuracy for LH2
- Does not provide real-time measurement during propellant outflow
  - Temperature measurements in helium supply must be delayed until thermal conditions have re-equilibrated
- Tank ullage temperature uncertainty must be small to achieve accurate gauging results

Radio Frequency Gauging

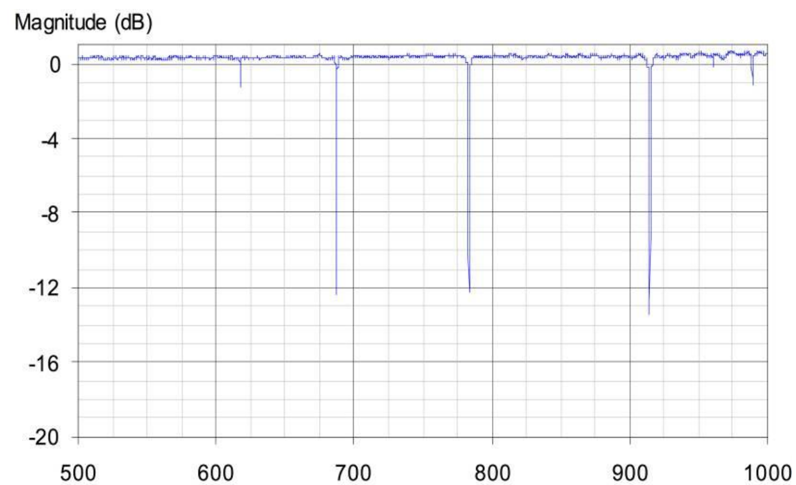
(Greg Zimmerli, P.I., GRC)

Objective: Measure propellant mass in a tank by characterizing the radio frequency (RF) electromagnetic resonant modes





Electric field simulation for TM011 mode in a partially filled dewar



Typical RF spectrum, showing the lowest resonant modes

Status & Issues with RF Gauging

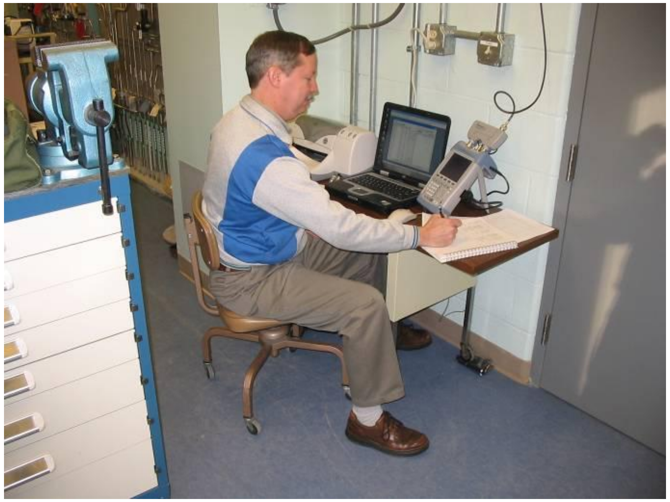
Status

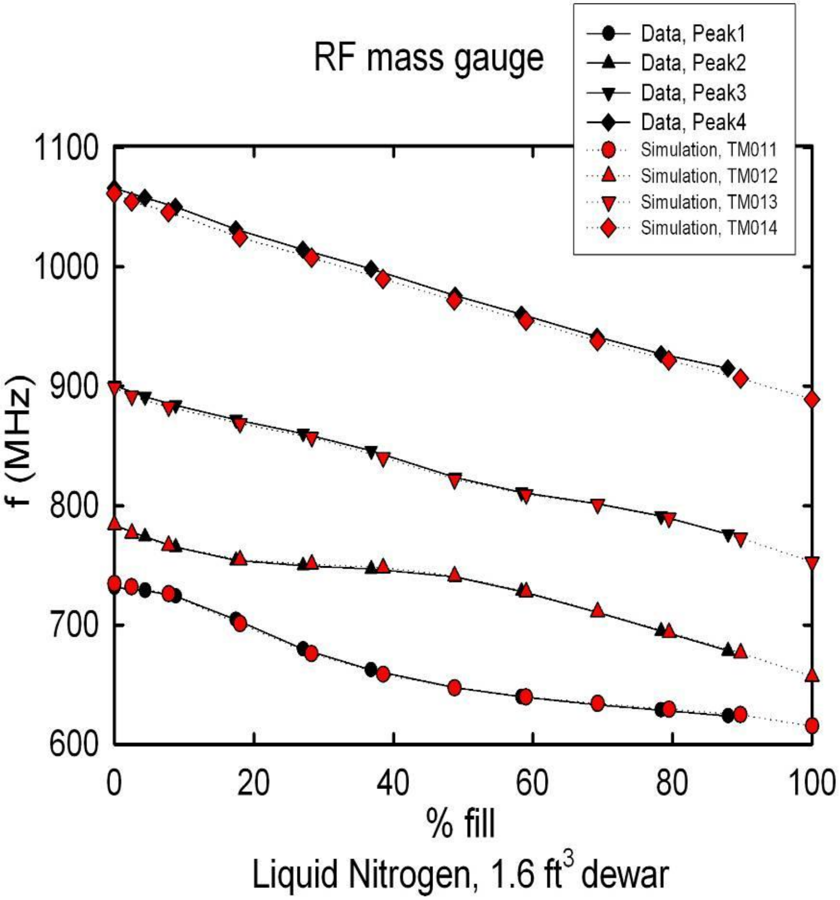
- Has extensive history, but no recent activity until GRC resumed work in 2005
- Work at GRC shows excellent agreement between experimental results (LO2 and LN2) and numerical simulations for simple tank geometries and settled liquid configuration
- Further testing with LO2 and LH2 planned for 2006
  - CEV project
  - Small-scale LCH4 testing also planned

Issues

- Numerical simulation capability must be proven for typical tank geometries and low-g liquid configurations
- Algorithm to accurately predict liquid mass from database of simulated results remains to be developed and validated

RF Testing at GRC





Closing Remarks

- Compression, Optical, and RF all show promise but each needs much more development and testing
- PVT gauging was the baseline for the CEV with LO2/LCH4
  - Is not fast and not as accurate as desired (esp. with LH2)
  - Can only be used if tank is pressurized with helium
- We are not in a current position of being able to confidently select the best gauging method
  - Need to continue parallel development of multiple gauging methods
- May need different gauging methods for different applications

Cryogenic Propellant Storage Technology Development

Dave Plachta

The Cryogenic Propellant Storage Challenge

Heat entering the propellant storage system warms the propellant and causes some vaporization resulting in tank pressure increase, thermal stratification, and venting losses (boil-off).

Approaches to minimize boil-off losses or achieve Zero Boil-off (ZBO):

<u>"Passive" Systems</u>

- Insulation
    - Foam (Convection)
    - Multilayer Insulation (Radiation)
    - Vapor Cooled Shields
- Shading and Deep Space View Factor
- Propellant Mixing
- Low Heat-Leak Structures
- Thermodymic Vent Systems

<u>"Active" Systems</u>

- Utilize components from a good "passive" design and add -
- Refrigeration (cryocoolers)
- Propellant heat exchangers
- Distributed cooling
    - Structure cooling
    - Cooled shields

Zero Boil-Off (ZBO) for Space Transportation

Requirement:

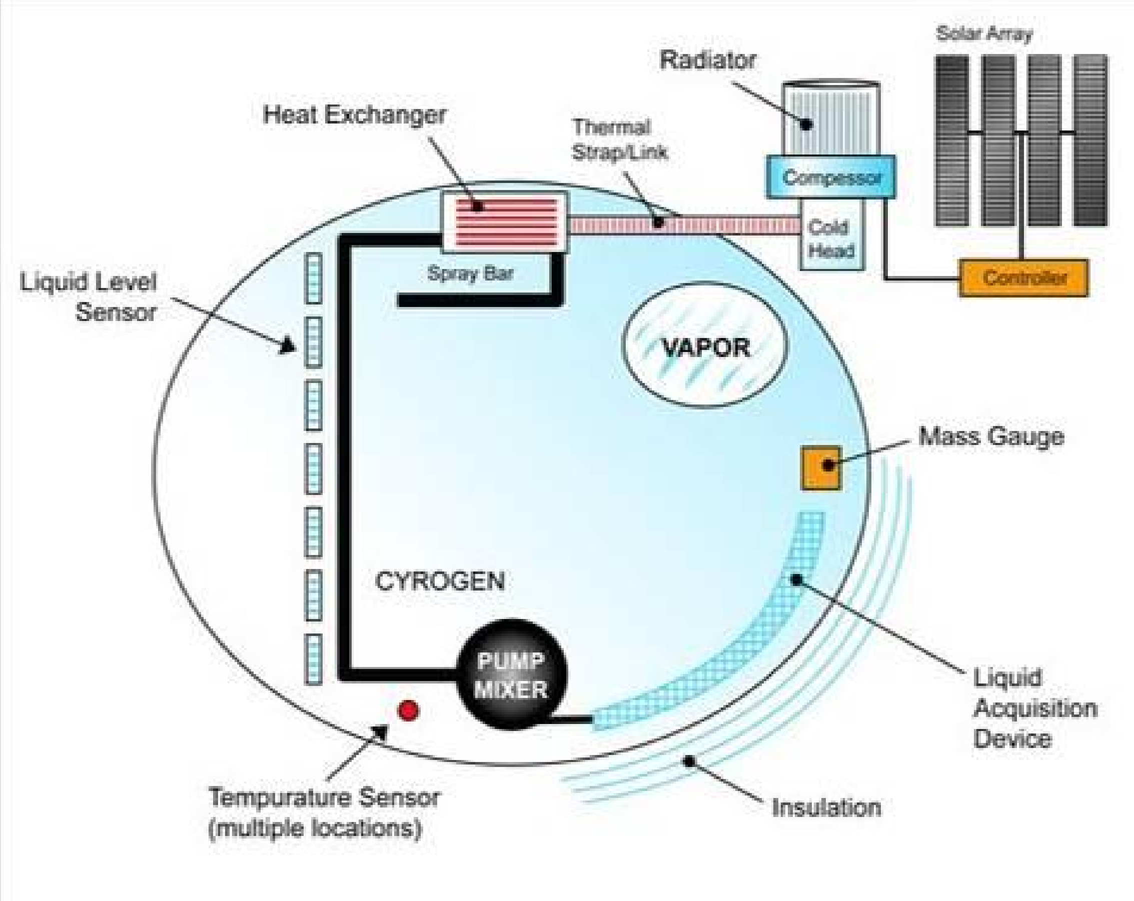
- Store cryogens in-space for years without boil-off

Approach:

- Take advantage of the tremendous advances in cryocooler technology and combine active (cryo coolers) and passive (multi-layer insulation-MLI) thermal control technologies to remove heat entering a cryogenic propellant tank and control tank pressure.
- Larger cryocoolers with heat exchangers can be used to liquefy propellants.

Benefits:

- Utilize high performing propellants in a “storable” configuration.
- In-space rendezvous and docking operations are enabled.
- Elimination of tank and insulation growth previously needed to accommodate boil-off.



Possible Cryogenic Tank In-Space Configuration

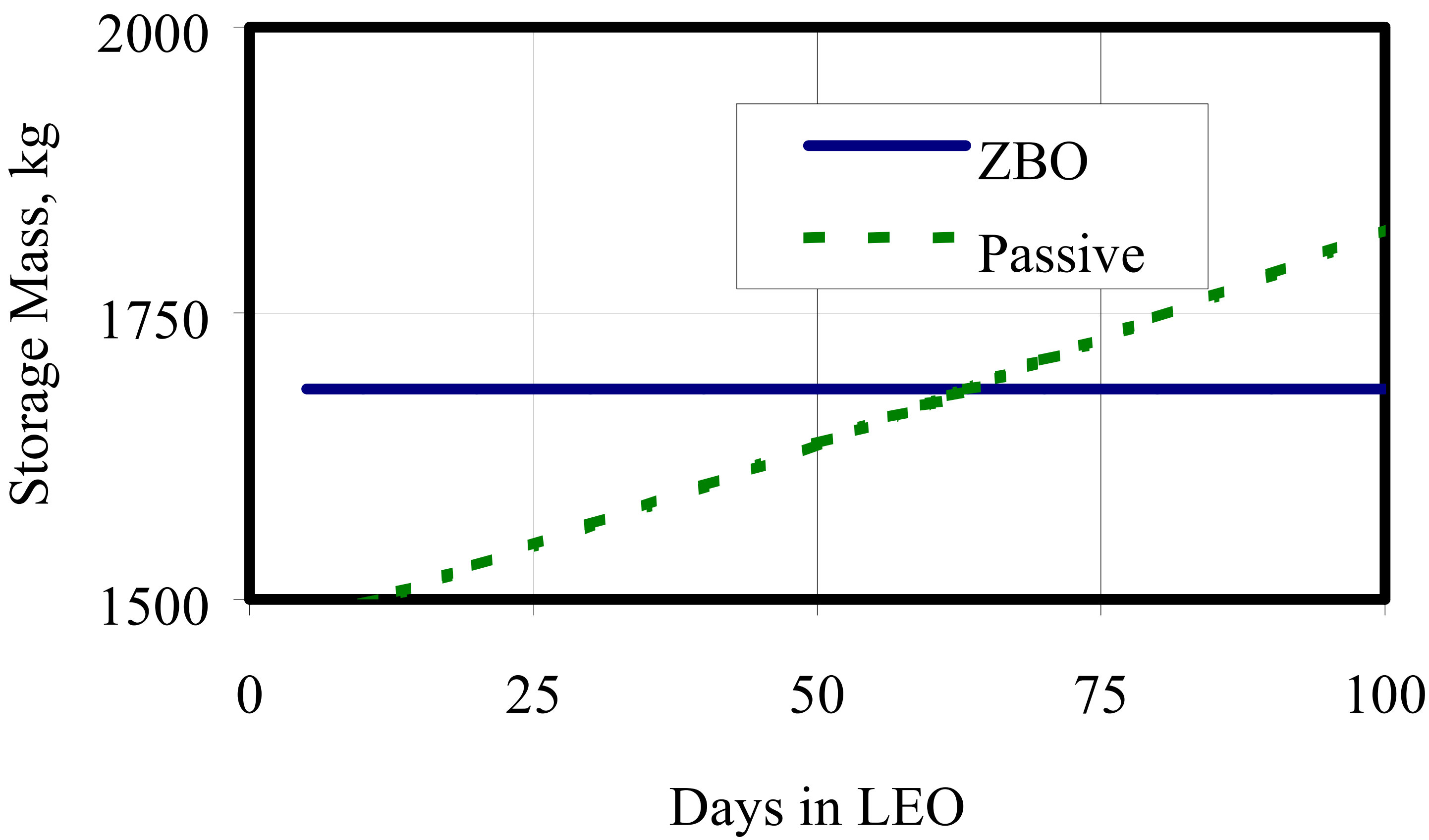
Analytical Studies

Cryogenic Analysis Tool (CAT)

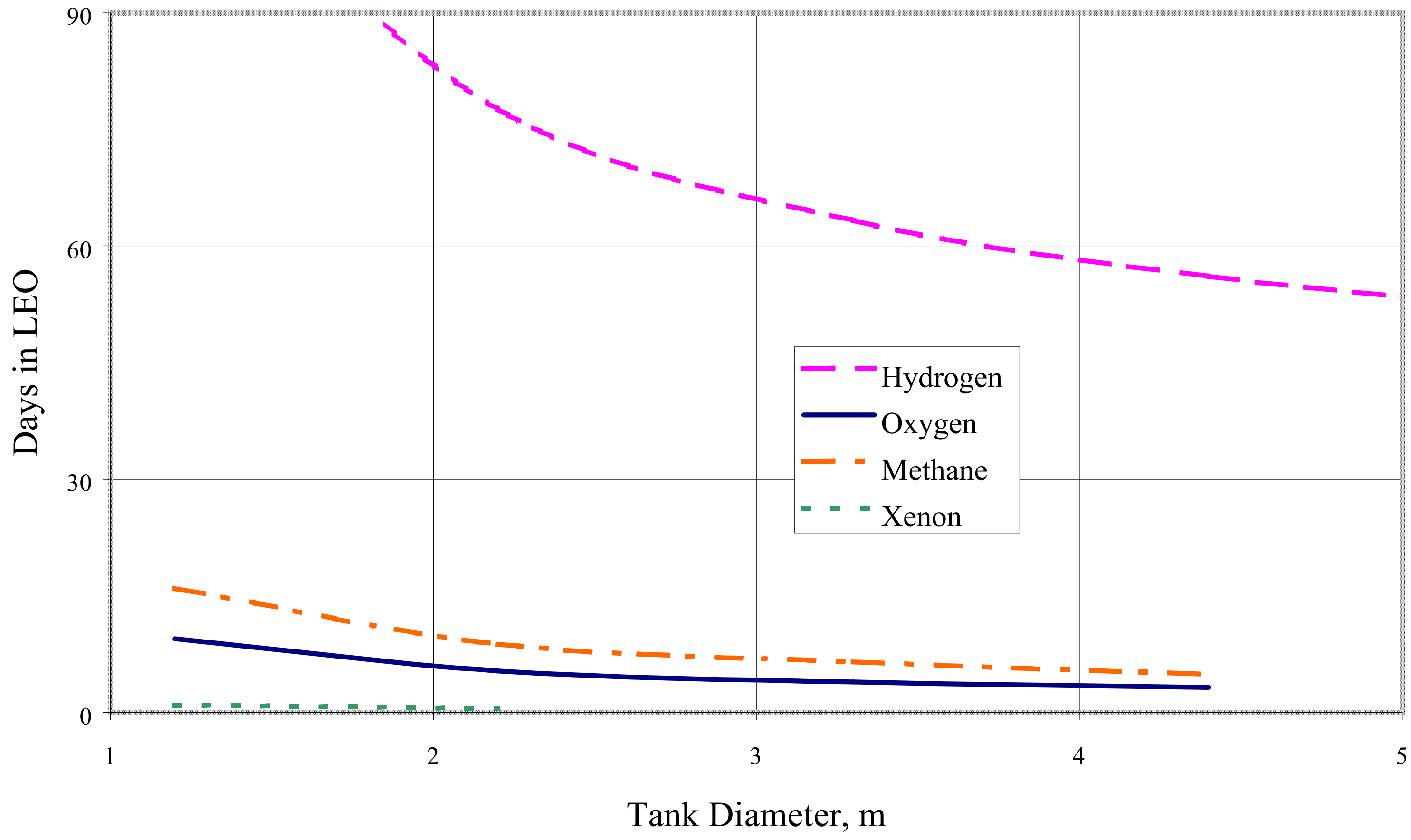
- Analysis of space vehicle configurations has driven zero boil-off technology development
- GRC is the agency leader in modeling of cryogenic propellant storage
- CAT is a spreadsheet based model created to perform cryogenic propellant storage system designs
  - CAT is a tool that determines passive and active storage system performance and sizes
- **Recent Cryogenic Storage Analyses with CAT**
  - Equal mass line ZBO payoff analysis
  - Deep space science mission cryogenic propellant applications
  - Cryogenic Propellant Depot applications

LH_2 Equal Mass Point

3.3 m dia spherical tank



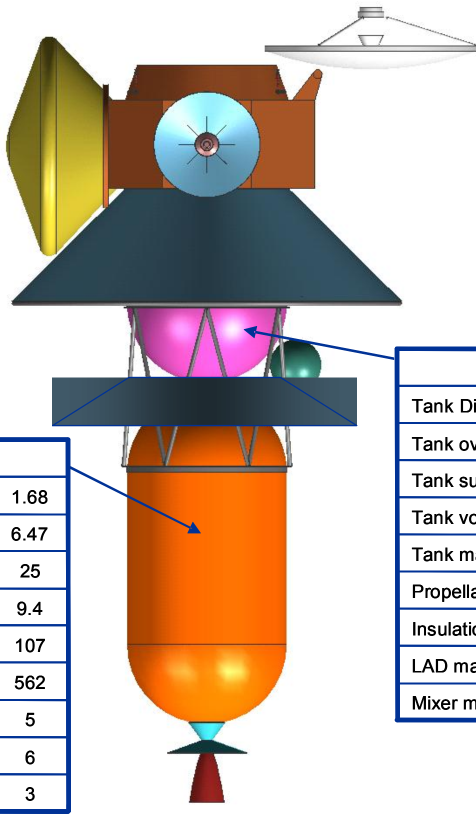
Equal Mass Lines



Deep Space Science Mission Applications

- JPL/GRC/ARC team bid and won a competitive task to evaluate cryogenic propellants with ZBO for deep space robotic missions
  - Two capability improvements were required for CAT
    - Time dependent solution
    - Detailed radiation model
  - Three example Science missions were analyzed to probe the benefits of cryogenic propellants (CAT was integrated into the JPL Team X process)
    - Titan Explorer (TEx)
    - Mars Sample Return/Earth Return Vehicle (MSR/ERV)
    - Comet Nucleus Sample Return Mission (CNSR)

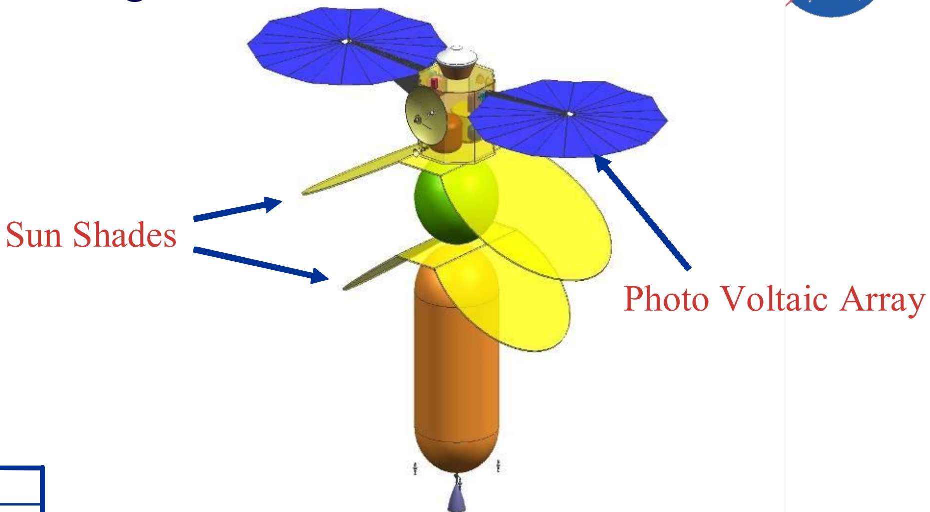
Science Mission Propellant Storage Configurations Considered



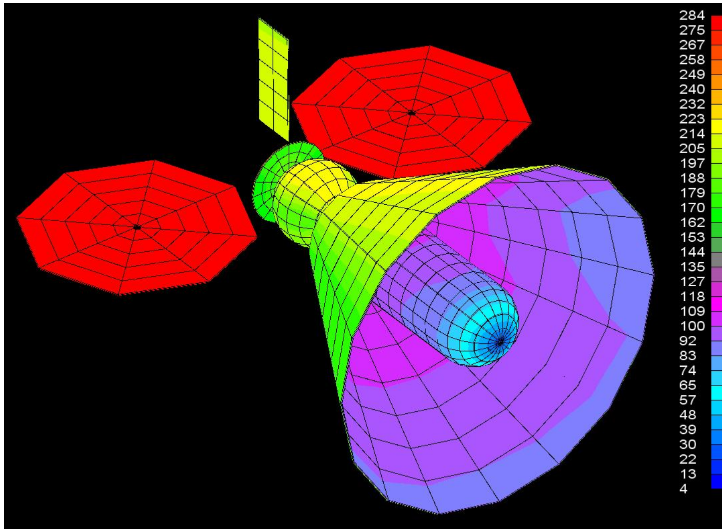
LH2 Tank	
Tank Dia. (m)	1.68
Tank overall length (m)	6.47
Tank surface area (m2)	25
Tank volume (m3)	9.4
Tank mass (Kg)	107
Propellant mass (Kg)	562
Insulation mass (Kg)	5
LAD mass (Kg)	6
Mixer mass (Kg)	3

LOX Tank	
Tank Dia. (m)	1.68
Tank overall length (m)	3.36
Tank surface area (m2)	9.8
Tank volume (m3)	2.9
Tank mass (Kg)	36
Propellant mass (Kg)	2798
Insulation mass (Kg)	3
LAD mass (Kg)	2
Mixer mass (Kg)	3

Titan Explorer Vehicle Configuration



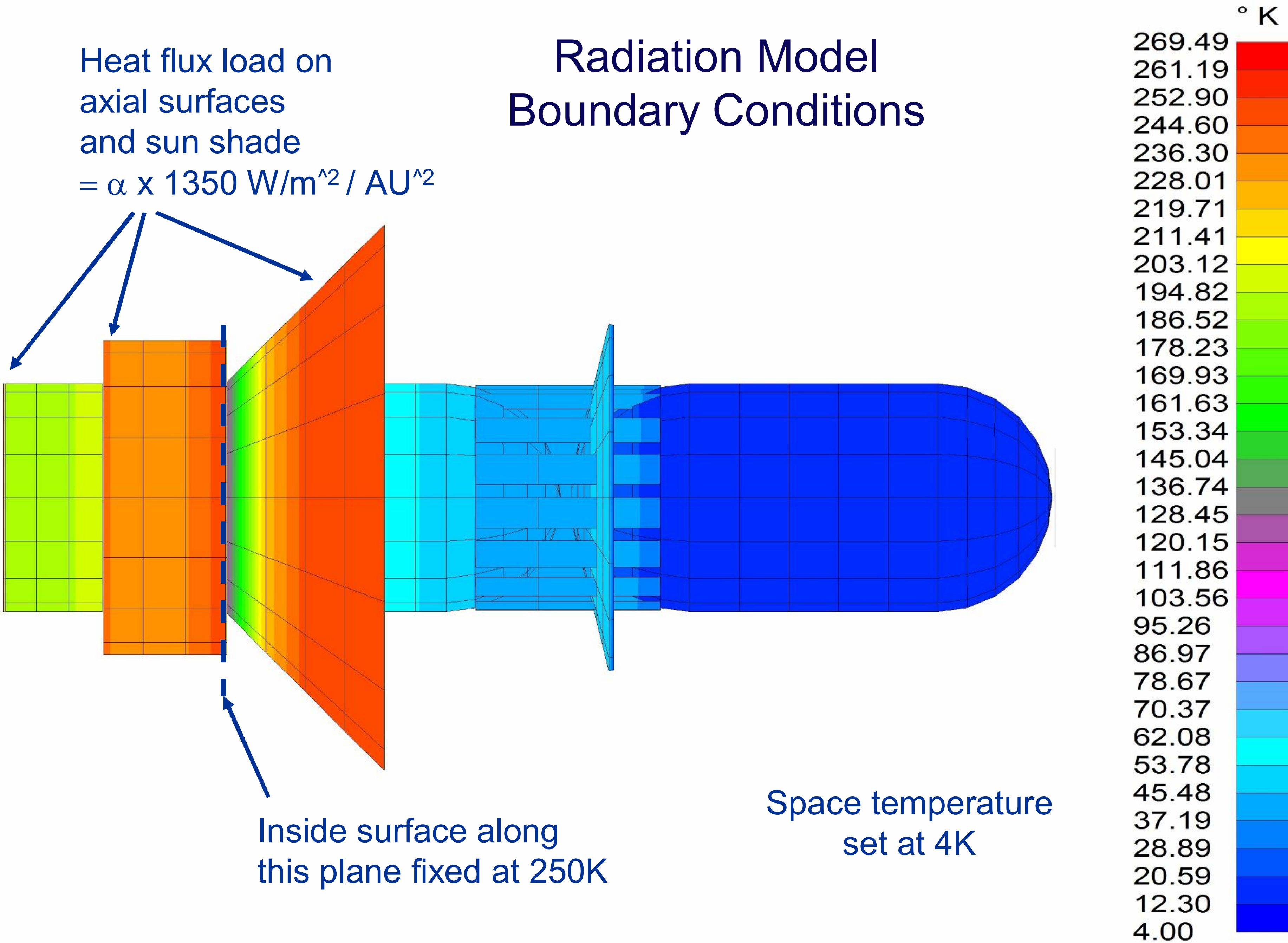
Comet Sample Return Shading Orientation



MSR-ERV Long Shade Configuration.
Radiation model shown with temperatures.

Radiation Model Boundary Conditions

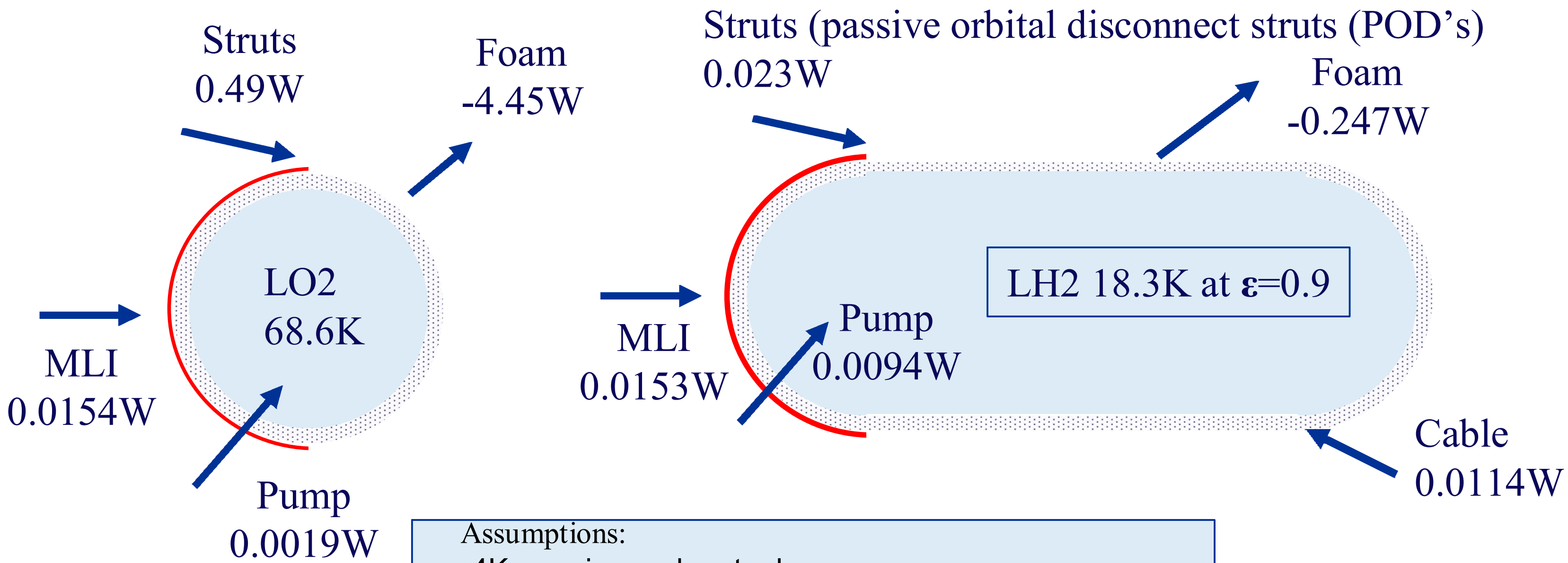
Heat flux load on axial surfaces and sun shade $= \alpha \times 1350\ W/m^{2} / AU^{2}$



Inside surface along this plane fixed at 250K

Space temperature set at 4K

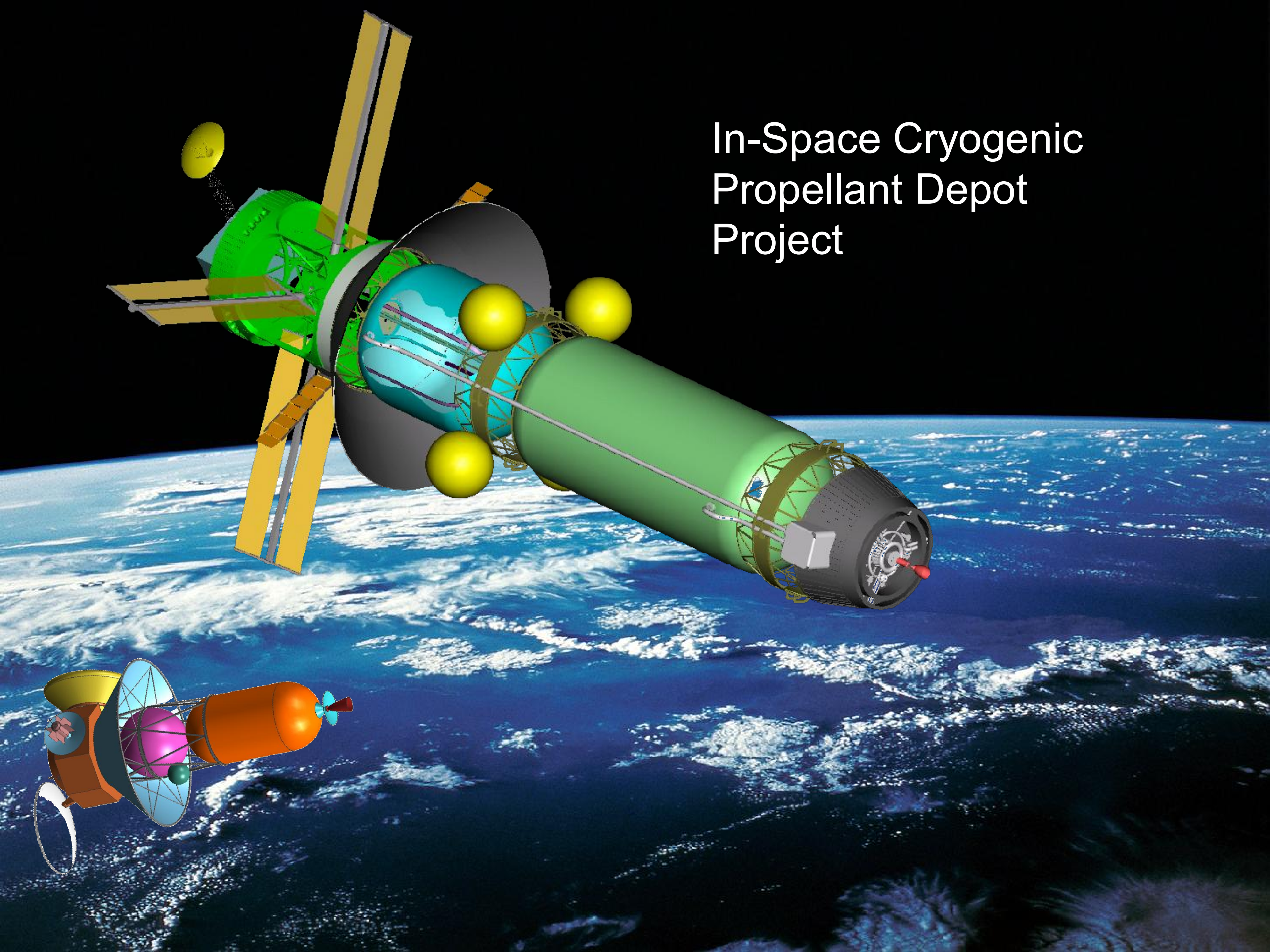
TEx Heat Leaks
Passive ZBO Achievable



Assumptions:
- 4K margin used on tanks
- All inner wall nodes fixed at uniform temperature
- MLI and foam heat leaks from finite difference model
- Iterated on temperature until heat balance achieved

- Using shades provided a limited deep space view dramatically reducing exterior temperatures
- LOX tank can act as a radiator and easily achieve ZBO, with no insulation
- LH2 tank can also be stored passively and achieve ZBO

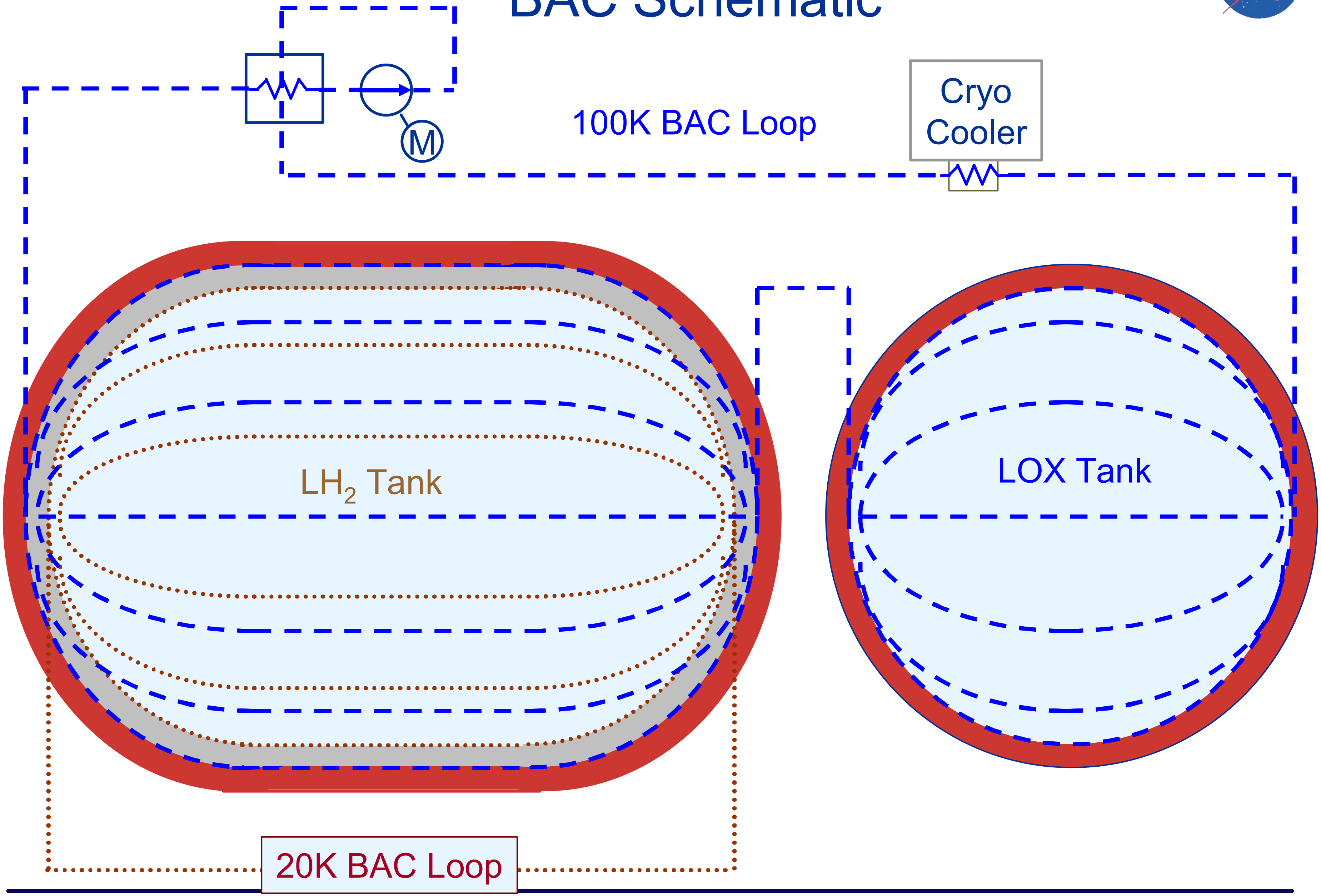
In-Space Cryogenic Propellant Depot Project



Depot Cryo Storage Activities

- Developed CAT Plus to define a thermal storage concept for an array of depot architectures
  - Identify best cryocooler integration concepts
  - Perform trade studies
- Cryocooler integration concepts considered:
  - Heat Pipes
  - Conventional
  - Capillary Pumped Loop Heat Pipe (LHP)
  - Advanced Cryogenic LHP
  - Wide Area Heat Pipe
  - Thermal Switches
    - Diode Heat Pipe
    - Differential Thermal Expansion
    - Actuated
    - Gas Gap
  - **Distributed Broad Area Cooling (BAC)**

BAC Schematic

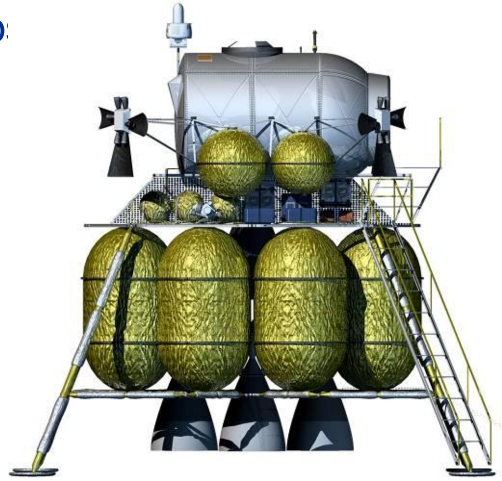


BAC Advantages

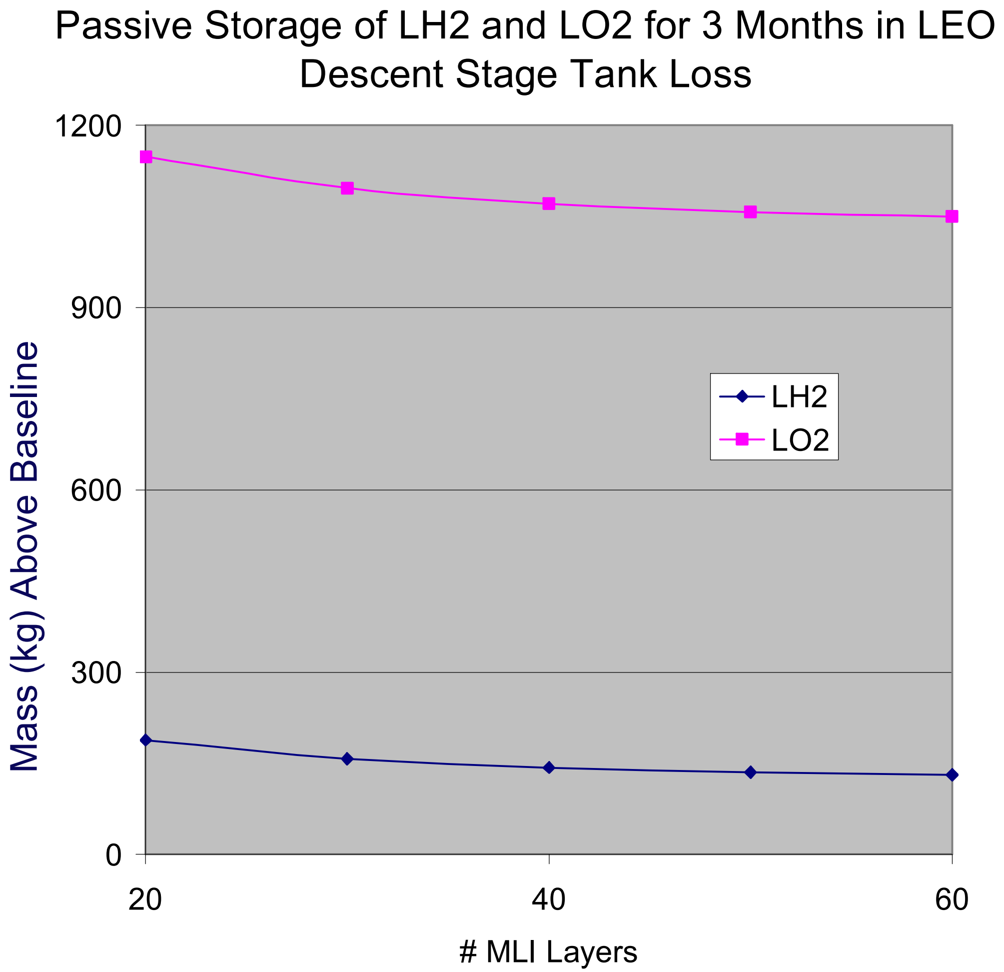
- BAC efficiently moves heat long distances to cryocooler
- BAC offers opportunity to integrate LO2 cryocooler with LH2 tank insulation
  - LO2 cryocooler technology is available today
  - LH2 100K shield reduces H2 boil-off by 70%
- BAC eliminates need for an internal tank mixer or destratification device for ZBO designs
- With compressor off, BAC thermally isolates cryocooler
- BAC offers opportunity to take advantage of cryocooler staging with BAC loop for each stage
- In μG, warm fluid is predicted to migrate to tank walls (Ref. M. Kassemi, et. al., *Zero Boil-Off Pressure Control of Space Propellant Tanks)*

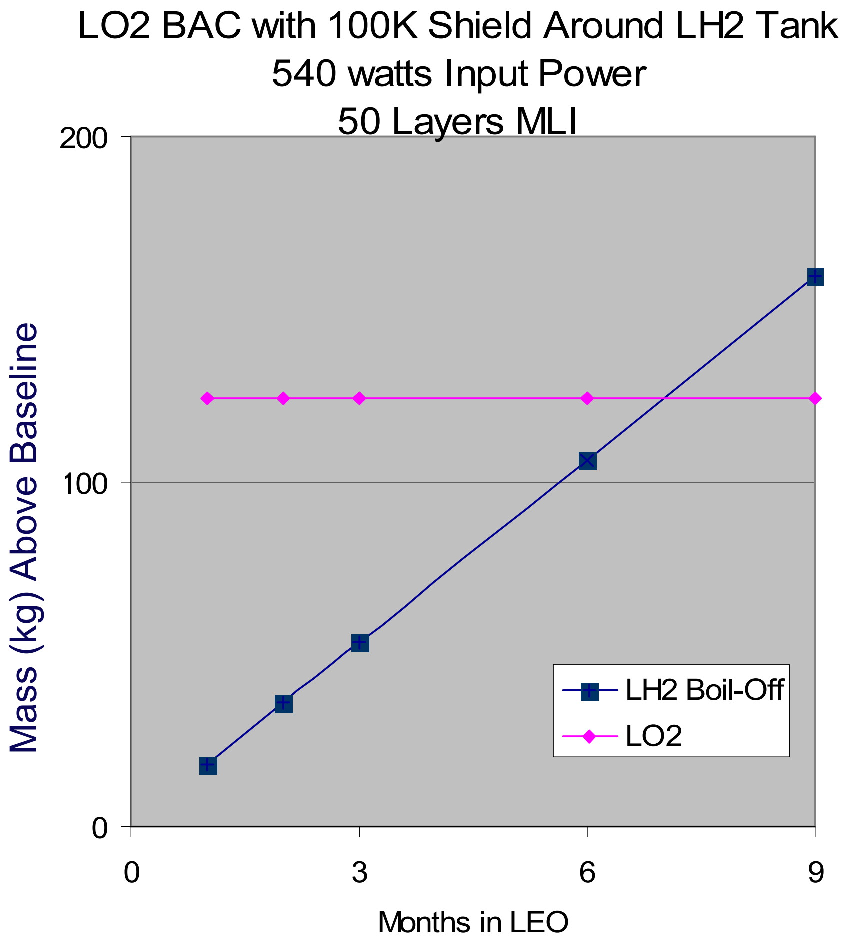
BAC Analysis Considerations

- Compare passive thermal storage compared to BAC concepts
- Net masses are compared
  - Propellant load, tank, and insulation mass baseline were subtracted out for comparison sake
  - *Tank and insulation growth to accommodate boil-off included*
  - *For ZBO solutions, radiator mass and solar array mass are included*
- Major assumptions:
  - 10 m circulation length, excluding tank loops
    - *Could be used to cool lines, struts, or other*
    - Radiation ht. transfer neglected
  - *He bottle cooled via BAC*
  - *One cryocooler and BAC/tank*
  - 2K drop through tubing
  - Parallel tubing loops
  - Shield temp drop between tubes <.5K
  - 400 psi compressor
    - He press. drop less than 5 psi
    - Assumes compressor rated for cryo temperatures
    - Assumes 60% compressor efficiency; 90% for motor



Passive vs. BAC with H2 Shield



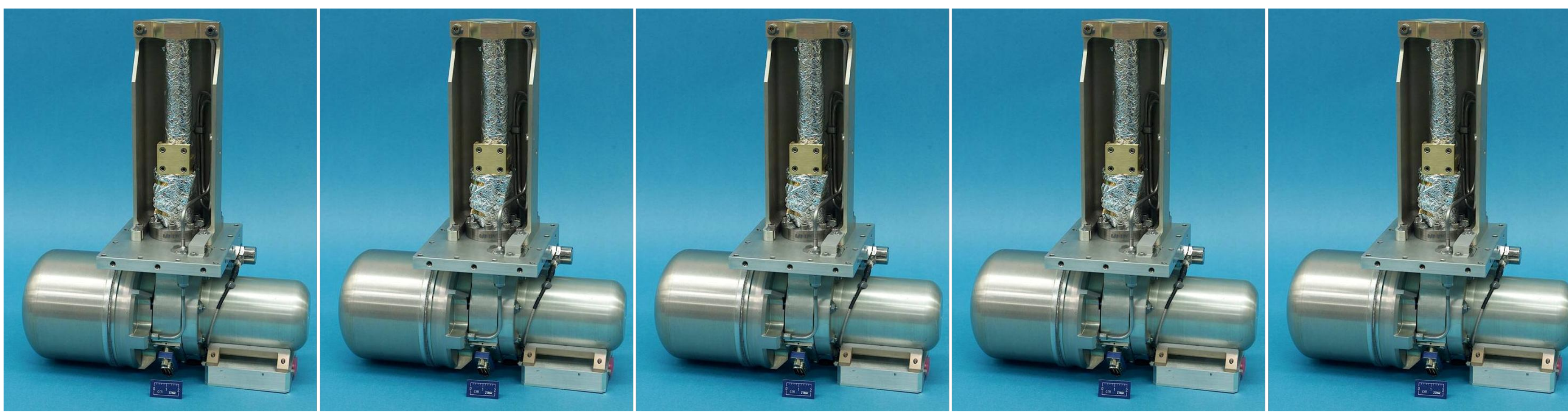


Mass Trade of Passive vs. LO2 BAC with H2 Shield

- *LO2 BAC/LH2 BAC shield dramatically reduces net mass (tank, propellant, and insulation mass subtracted out) for decent stage:*
  - Passive case:
    - 135 kg/tank LH2
    - 1060 kg/tank LO2
    - Total: 3740 kg
  - LO2 BAC/LH2 BAC Shield
    - 50 kg/tank LH2
    - 125 kg/tank LO2
    - Total: 570 kg
- Similar results expected for cryo option for ascent stage

Could We Develop LO2 BAC Today?

- 5 of these NGST 95K HEC cryocoolers combined with BAC shielding would be able to meet these predicted loads
  - 4 kg coolers, 140 watt compressor
  - 2 liter pop bottle size
- Requires H_2 shield development
- Requires component, integration, and system testing



Experimental Studies

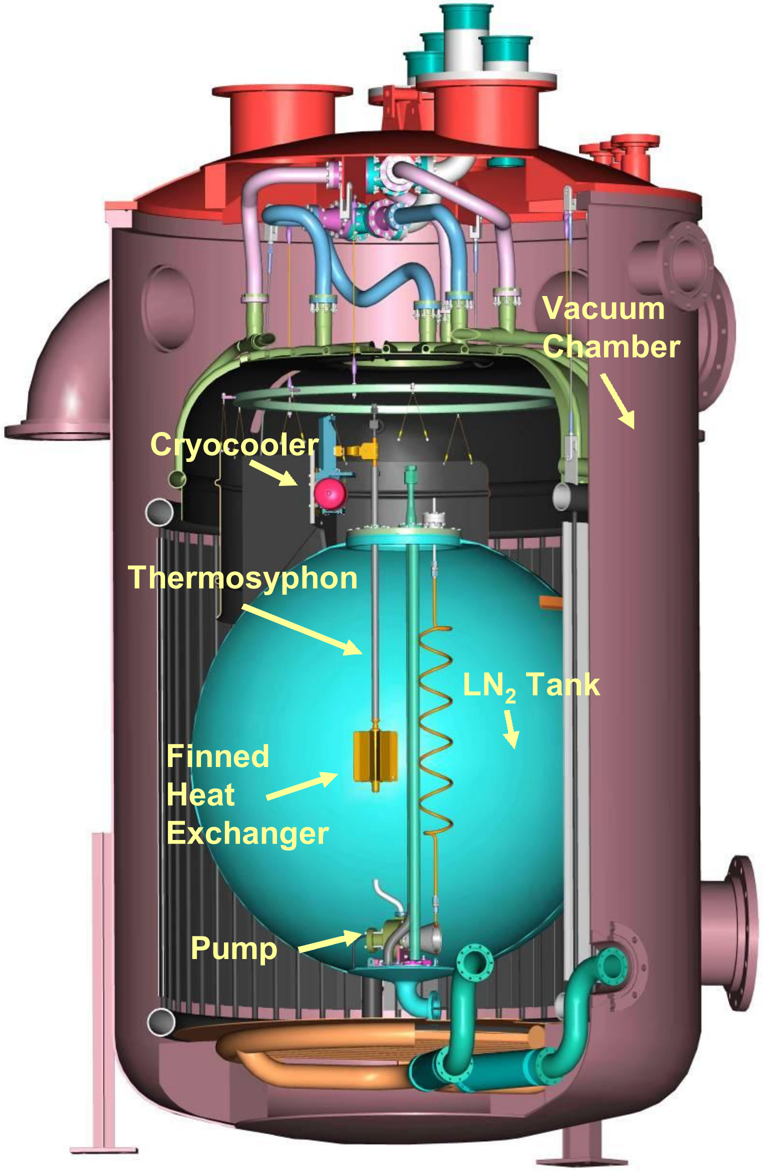
Advanced ZBO Development Ground Test

Requirement:

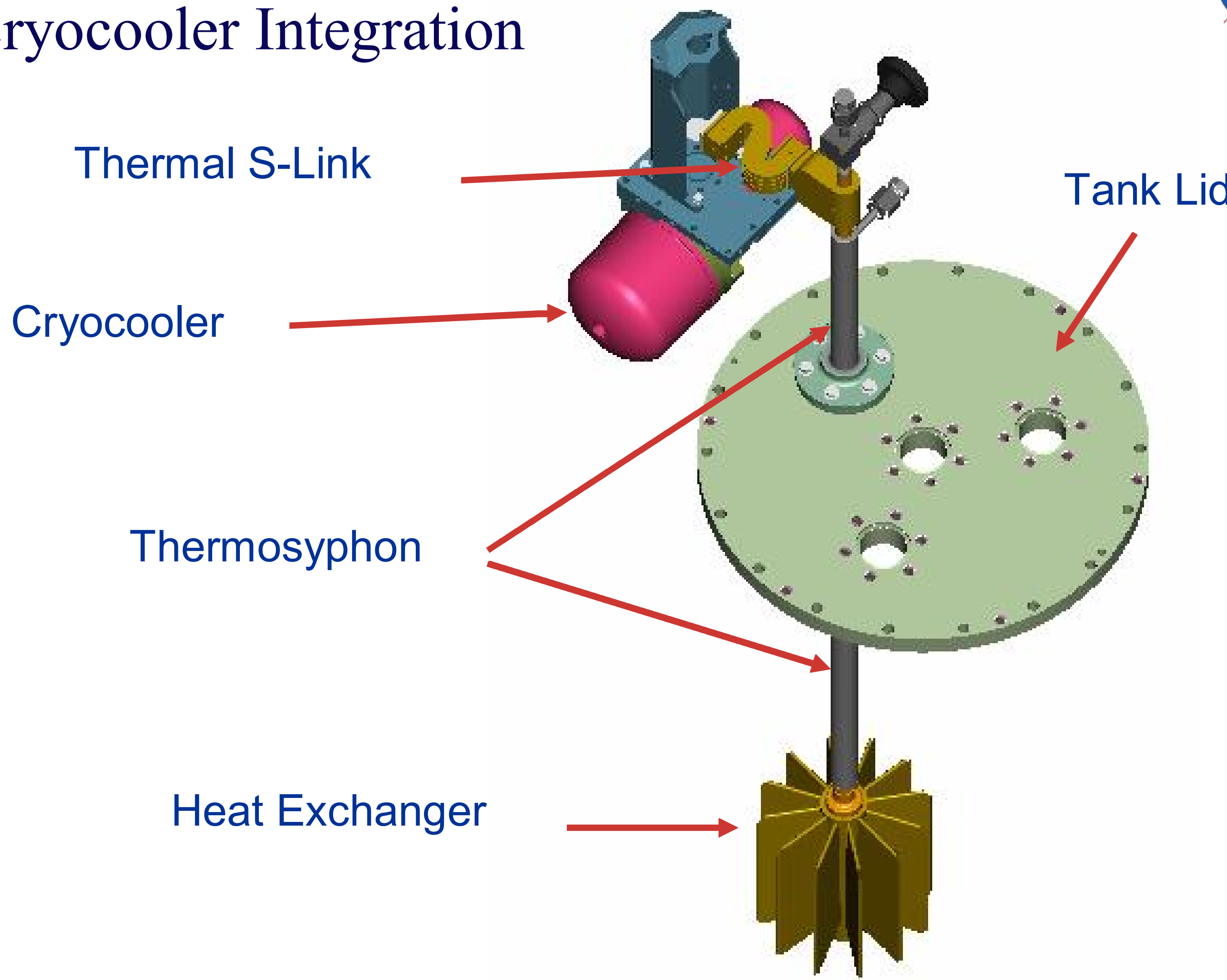
- Integrate flight-type components necessary for ZBO into cryogenic propellant tank and test

Approach:

- Integrate flight-type or flight simulated cryocooler, power system, radiator, and heat exchanger with a cryogenic propellant tank.
- Utilize TRW cryocooler with the 1.4m dia tank with 34 layers MLI, filled with LN2.
- Perform test in SMIRF vacuum tank with cold wall surrounding test tank.
- Integrate mixer with heat removal system in tank



Cryocooler Integration



Planned Future Activities

- Continue evolving CAT model and publish results
- Support Lunar Architecture Requirements Preparatory Study led by Langley
  - Perform long-term storage analysis on EDS, descent stage, and cryo ascent stage options
- Higher Fidelity Models (Computational Fluid Dynamics)
- Develop BAC
  - Integrate and test BAC with cryogenic propellant storage tank
    - Ensure reliable contact and heat transfer from tube to tank
  - Develop cryogenic temperature circulator
  - Perform trade and development activity on He accumulator
  - Develop BAC MLI interstitial shield
  - Develop and test penetration/strut BAC or vapor cooling concept
  - Integrate BAC with multi-stage cryocoolers
- Develop tank shading concepts and test
- Develop detailed tank support strut model and test